Technical papers in hydrology 5 Part II

Combined heat, ice and water balances at selected glacier basins

Part II : specifications, standards and data exchange

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to the International
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Preface

The International Hydrological Decade (IHD) 1965–74 was launched by the General Conference of Unesco at its thirteenth session to promote international co-operation in research and studies and the training of specialists and technicians in scientific hydrology. Its purpose is to enable all countries to make a fuller assessment of their water resources and a more rational use of them as man's demands for water constantly increase in face of developments in population, industry and agriculture. In 1972 National Committees for the Decade had been formed in 107 of Unesco's 129 Member States to carry out national activities and to contribute to regional and international activities within the programme of the Decade. The implementation of the programme is supervised by a Co-ordinating Council, composed of twenty-one Member States selected by the General Conference of Unesco, which studies proposals for developments of the programme, recommends projects of interest to all or a large number of countries, assists in the development of national and regional projects and co-ordinates international co-operation.

Promotion of collaboration in developing hydrological research techniques, diffusing hydrological data and planning hydrological installations is a major feature of the programme of the IHD which encompasses all aspects of hydrological studies and research. Hydrological investigations are encouraged at the national, regional and international level to strengthen and to improve the use of natural resources from a local and a global perspective. The programme provides a means for countries well advanced in hydrological research to exchange scientific views and for developing countries to benefit from this exchange of information in elaborating research projects and in implementing recent developments in the planning of hydrological installations.

As part of Unesco's contribution to the achievement of the objectives of the IHD the General Conference authorized the Director-General to collect, exchange and disseminate information concerning research on scientific hydrology and to facilitate contacts between research workers in this field. To this end Unesco has initiated two collections of publications: 'Studies and Reports in Hydrology' and 'Technical Papers in Hydrology'.

The collection 'Technical Papers in Hydrology' is intended to provide a means for the exchange of information on hydrological techniques and for the co-ordination of research and data collection.

The acquisition, transmission and processing of data in a manner permitting the intercomparison of results is a prerequisite to efforts to co-ordinate scientific projects within the framework of the IHD. The exchange of information on data collected throughout the world requires standard instruments, techniques, units of measure and terminology in order that data from all areas will be comparable. Much work has been done already towards international standardization, but much remains to be done even for simple measurements of basic factors such as precipitation, snow cover, soil moisture, streamflow, sediment transport and ground-water phenomena.

It is hoped that the guides on data collection and compilation in specific areas of hydrology to be published in this collection will provide means whereby hydrologists may standardize their records of observations and thus facilitate the study of hydrology on a world-wide basis.

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FOREWORD

The IHD project concerned with the combined heat, ice and water balances at selected glacier basins marks an important step in broadening the understanding of snow hydrology, high mountain and glacier hydrology, and the relation of glacier variations to changes in climate. The specific objective of the project is to obtain sufficient information to define and understand heat, ice and water balances and how they change with time at a number of glacier basins situated in widely differing environments in many parts of the world.

In this second part of "Combined heat, ice and water balances at selected glacier basins", the emphasis is on specifications and standards for types, locations and timing of measurements, with particular attention given to heat balances. It is published with the intention of providing a basis for international co-operation in attaining standardized measurements of all three glacier balances. This project is intimately linked to many other Decade projects such as the world inventory of perennial ice and snow masses, variations of existing glaciers and the world water balance. Guidance materials to these may also be found in other publications in the 'Technical Papers in Hydrology' collection. The project is also an extension of the representative and experimental basins programme, a cornerstone of the IHD programme since a glacier basin is a hydrologic basin in which the effects of snow and ice reach their ultimate development. Thus, the project demonstrates the interdependence of all hydrological research and the importance of international co-ordination of studies in scientific hydrology.

This technical guide was prepared by a Working Group of the International Commission of Snow and Ice of the International Association of Scientific Hydrology, under the chairmanship of Dr. M.F. Meier. A subcommittee of this Working Group dealt specifically with heat balances. Unesco gratefully acknowledges this work.

1 INTRODUCTION

During the International Geophysical Year, many useful glacier mass balance results were obtained. However, very few stations produced heat balance data which could be directly compared with those from any other station (Hoinkes, 1964). In the years since the IGY, no major solutions to the problem of making accurate and standardized heat balance measurements have appeared. It is now apparent that proper measurement of all components in a heat balance involves considerable expense, as well as sophisticated instrumentation and highly competent scientists, and it is not likely that more than a very few nations can afford to do this work.

Therefore, this Combined Balances project of the International Hydrological Decade is built around two kinds of stations:

a. A large number of Standard Stations will produce data on ice and water balances, as well as basic data for the correlation of meteorological and glaciological conditions. A certain minimum number of prescribed instruments will be operated to obtain daily measurements over a major portion of the ablation season at one location on a glacier. Other measurements will be made to extend the data coverage over a larger area or the complete drainage basin at monthly intervals. The minimum level of precision of the daily and monthly values will be specified, and tabulations of data will be exchanged between projects through the World Data Centres and the Permanent Service on the Fluctuations of Glaciers.

b. A limited number of Special Stations will be established to study heat and mass exchange processes, and to develop procedures for relating the simple measurements obtained at Standard Stations to actual heat exchange conditions. At these Special Stations, all of the daily measurements prescribed for Standard Stations will be made, and in addition complete, modern heat balance instruments will be operated. These will be of sufficient precision and sophistication so that all components of the heat balance are measured with confidence. These results will then be used to verify existing techniques and to derive new procedures for analyzing the data obtained at Standard Stations in terms of more meaningful heat balance and glacier-meteorological relationships.

The philosophy is to compute, at frequent intervals, approximate heat balances from simple data, using a modified aerodynamic approach, at one site at each standard station; to extend these results to cover larger areas by simpler measurements at less frequent intervals; and to calibrate and refine the standard station heat balance computations by means of a few special stations where heat balances will be determined by rigorous, modern methods such as the eddy correlation technique. All levels of activity, therefore, are of equal importance to the total programme.

Standard Stations should include, where possible, observations over a whole glacier drainage basin. Only in this way can heat, ice and water balances be directly compared. However, in some areas this may not be possible: the glaciers are too large, or the financial and economic resources are too small. In order to permit investigations in these areas, compromise programmes will be allowed. These could take the form of intensive heat and ice balances measured at just one point or in one small area, coupled with or without water balances measured over a larger or different area. Such work will not be discouraged, but it should be kept in mind that such an investigation is susceptible to large absolute errors; the self-checking feature of complete balances is missing. On the other hand, rigid adherence to whole-glacier measurements might limit the programmes in some areas to tiny glaciers existing just at the equilibrium line altitude, and this is not a desirable sampling of glacier-atmosphere interactions.

Much of the effort for Standard Stations will involve daily measurements at a single observational site. Other measurements, made less often, will extend over the larger area of interest.

HEAT BALANCE

Daily observations at one site

These observations are preferably to be taken at a centrally located site in the accumulation zone of the glacier but near its lower limit, where the surface is nearly horizontal or has a relatively even slope, a representative surface condition, and, if possible, an exposure and horizon reasonably representative of the glacier as a whole. If this location is impractical, another location representative of a larger homogeneous area may be chosen. The site is to be described as a Station Description. If a second site can be operated, it should be in the middle of the ablation area.

The measurements listed below are to be taken continuously during the major portion of the main ablation season. Longer periods of measurement are desirable, and in some areas may be essential. A shorter period of observation is not recommended, but is permissible if appreciable ablation does not go unmeasured. The following daily observations are prescribed; the frequencies of observation are given in Table 1.

1. Global solar radiation.-- This should be measured with a pair of glass-covered pyranometers (e.g., Kipp or Eppley type) and recorder. The instruments must be maintained in an absolutely level orientation, one pointing up and one pointing down, and the glass domes carefully cleaned of hoarfrost, rime, or snow accumulations. The instruments should be located so that no shadows of other installations fall on them for more than a few minutes per day. The instruments, recorder, and computation procedure should be capable of defining daily sums of incoming and reflected solar radiation with a standard error not greater than 1 MJ/m^2 (25 ly). Report daily incoming and reflected sums in MJ/m^2, to nearest 0.1, 0.5, or 1 MJ/m^2 depending on

precision of instrument, or report incoming radiation and albedo. If radiometers cannot be operated, sunshine duration must be recorded, and it is very important to specify the type of instrument used to measure sunshine duration. A sunshine duration meter might also be operated to provide data in case of radiometer/recorder failure.

Table I. -- Types and frequencies of observations to be performed at the main site.

Note: -- Frequency of observations defined as: c, continuously through season; 5c, continuously for selected 5-day periods; $\frac{1}{2}$d, twice daily; $\frac{1}{4}$d, four times a day; d, daily; 5d, every 5 to 10 days.

Type of observation	Standard station			Special station
	Minimal programme	Recommended programme	Optional programme	Suggested programme
Radiation				
Sunshine recorder	c			c
Glass-covered pyranometers (2)		c	c	c
All-wave net radiometer			c	
Long-wave radiometers (2)				c
Temperature				
Air at 2 m, thermograph in shelter	c	c		c
Air, profile 0.5-2 m, thermistor or thermocouple, recording			5c	c
Snow surface (glass thermometer)		d		c
Snow at 0, 2, 5, 10, 20 cm below surface, recording			5c	c
Nocturnal crust thickness	d	d	d	d
Humidity				
Hygrograph at 2 m in shelter	d	c	c	c
Profile 0.5-2 m wetted thermistors, thermocouples, or more sophisticated sensors, recording			5c	c
Cloud cover	$\frac{1}{2}$d	$\frac{1}{4}$d	$\frac{1}{4}$d	$\frac{1}{4}$d
Wind				
Daily totals at 2 m	d	$\frac{1}{2}$d		
Recording at 2 m			c	c
Profile 0.5-2 m, recording			5c	c
Wind direction, 2 m		d	5c	c
Precipitation				
Standard gauge	d	d	d	c
Measurements on ground after each snowfall	d	d	d	d
Evaporation/condensation				
Lysimeter			5c	d
Blowing snow				
Snow drift meter			d	d
Air pressure				
Aneroid barometer		d		
Barograph			c	c
Ablation				
Bulk ablation	5d	d-5d	d	d
Liquid water content				d
Snow surface characteristics	5d	5d	d	d

2. Air temperature.-- Air temperature sensors are to be properly shielded against errors due to incident and reflected solar radiation. Furthermore, they should be well ventilated. Outputs should be recorded continuously or at intervals of not more than 30 minutes. The air temperature sensor should be maintained at 2 m & 20 cm above the mean show surface, and it should not be located down the prevailing wind direction from another large installation. Daily means should be recorded to 0.5°C, and these means should have an absolute precision indicated by a standard error of 1°C or less.

3. Minimum snow surface temperature.-- A simple minimum-registering glass (not plastic) thermometer, laid directly on the snow surface and not shielded against radiation, will suffice. Daily minimum values should not exceed 0.5°C.

4. Nocturnal crust. -- The thickness of the nocturnal crust should be measured each morning to an accuracy of 1 cm and reported to the nearest cm.

5. Humidity.-- This should be measured at a height of 2 m & 5 cm above the snow. A high quality, recording instrument is recommended, and the type of instrument used should be described. A ventilated psychrometer is required in order to calibrate the sensor used for the continuous record. Values should have a standard error at any instant of 10 per cent relative humidity or less, and daily means should be recorded to 1 per cent.

6. Cloud cover.-- Observations of cloud cover type and amount should be made at least twice a day, and preferably four times a day. Average values of cloud cover amount for the daylight portion of each day should be reported. In case of fog, times of beginning and ending at the main site should be recorded.

7. Wind speed.-- A well calibrated anemometer should be mounted on a stand so that its axis is kept vertical (& 10°) and the cups are maintained at an elevation of 2 m & 20 cm above the mean surface. It should be located up wind and some distance away from other installations. The instrument should have a precision (standard error) of 5 per cent or less for winds in the range 1-15 m/s. If a recording anemometer is not used, the daily wind run totals should be read at standard times twice a day. Tabulate mean wind speeds for the day to the nearest 0.1 m/s. The wind direction should also be measured at the two standard times.

8. Precipitation.-- A standard precipitation gauge with wind shield should be mounted vertically (& 5°) with an orifice of at least 200 cm^2 at 1.5 m above the snow surface. When precipitation occurs as snow, the gauge reading will be very inaccurate and supplemental readings of new snow depth and density on the glacier surface are essential. These supplemental measurements should be taken over a broad area in the vicinity of the precipitation gauge to get a valid average. Snow and other forms of frozen precipitation should be separated on the basis of direct observation. For a more complete discussion on the proper measurement of precipitation see Unesco/IASH (1970a). Every effort should be made to derive daily totals of precipitation accurate (standard error) to 2 mm of water. Tabulate to nearest millimetre. The dimensions of the precipitation gauge and the type of wind shield should be reported.

9. Air pressure.-- An aneroid barometer, read daily, or a recording barograph is recommended. These data are useful for computing specific humidity and calibrating a hygrograph with a psychrometer.

10. Ablation.-- Measurement of this parameter is most difficult and will require the greatest care and attention of the observer. A measuring procedure sufficiently precise to give daily values of water-equivalent accurate to at least 4 mm (standard error), which are representative of the measurement site is desired. This requires measurements at many closely spaced points to properly define the surface lowering, density-depth profiles taken at appropriate intervals (daily to every few days) depending on the rate of change of density with time, and proper attention to such problems as the refreezing of water in the snow and the settlement of snow around ablation stakes or the supports of ablation-measuring devices (LaChapelle, 1959). The required number of points (which may be as few as 10 or as many as 100) should be determined by measuring ablation at 10 to 20 points, determining the mean daily ablation and the standard deviation of individual values from the mean, and applying a simple statistical analysis (e.g., Untersteiner, 1961, p. 159-160) to determine the required number of sample points for a 90 per cent probability of determining the mean within the required 4 mm of water-equivalent. This experiment should be repeated as the snow surface roughness changes during the season. By arranging the points along a line parallel to the wind direction, valuable information on the surface roughness parameter (z_0) can be obtained. Depending on the amount of ablation, the characteristics of the snow, and the availability of skilled observers, it may or may not be possible to make daily observations accurate to 4 mm of water-equivalent. If this accuracy cannot be obtained, then careful ablation measurements at less frequent intervals (every 5 to 10 days) are recommended. Less accurate daily measurements are not recommended. Report daily or 5-10 day totals in millimetres of water-equivalent.

11. Snow surface characteristics.-- A description of the character of the snow surface should be made every 5-10 days, or daily if the surface conditions are changing. This should include roughness, type of relief (such as sastrugi or sun cups), wetness, dirt, surface water run-off, and so forth.

12. Additional measurements at the main site.-- If at all possible, long-wave or all-wave radiometers, lysimeters to measure evaporation/condensation or ablation, snow drift meters, and liquid-water content measuring devices should be employed. These cannot be considered essential to all programmes, because of the expense involved.

Other observations

In order to extend heat balance results from the main site to cover a larger area, the following measurements need to be performed. It is best if these are done on the first day of each month during the main ablation season. If the drainage basin is not too large or inaccessible, these observations should cover the entire area.

1. Maps should be drawn of the distribution of snow, firn, and ice over the basin. Percentages of snow, firn, and ice in relation to the measured area should be reported on the first day of the month, and should be

correct to a standard error of 5 per cent of the total basin area.

2. The mean albedo of snow, firn, and ice should be measured at a sufficient number of points to derive a mean value for each type of surface accurate to 0.05 (standard error). This can be done with a portable pyranometer of the same type used at the main site.

3. By use of a Tagbogenmesser,[*] computation from a topographic map, or other technique, the percentage of total possible solar radiation incident on the snow or ice surface should be measured at at least 20 points scattered over the drainage basin, and values computed for the first day of each ablation season month.

4. Snow temperature/depth profiles to depths of 5 m or more should be taken at about 5 locations over the drainage basin, on about the first day of the month, as long as subfreezing temperatures exist. These temperatures should be accurate to 0.5°C. In some areas, these temperatures should also be measured in ice.

5. Air temperature should be recorded at 2 m above a ridge crest or mountain top, well away from the influence of the glacier wind or localized inversions. The sensor, height above ground, and accuracy should be similar to the temperature sensor at the main site. If possible, humidity measurements could also be made at this location.

6. If possible, 2 m air temperature should also be measured at a low altitude in or near the drainage basin, with a similar instrument.

7. Precipitation should be recorded at at least two locations in the drainage basin, away from the main site, and with similar instruments including wind shields. A larger number of storage precipitation gauges is preferred. The catch in those gauges should be checked against actual measurements of snow on the ground, and the necessary corrections applied to the results.

ICE BALANCE

Ice balance data cannot be obtained on a daily basis (except for ablation at one site), but will be collected at intervals of about once a month during the ablation season. Measurements should be scheduled so that a minimum of interpolation will be necessary to report ice balance quantities as of the first day of each month. Totals for the beginning and end of each balance year are essential; monthly values during the main ablation season are strongly recommended.

In general, the measurement technique should be such that a precision of 5 per cent (standard error) can be obtained for directly measured quantities at individual points.[**] Enough measuring points are required so that area integrations are also accurate to about 5 per cent, making a total precision of area-averaged quantities of about 9 per cent. This may require from 20 to 50 points (or even more) per basin depending on the roughness of the surface and the spatial dispersion of ice balance quantities. The required number of measurement points will have to be determined by each investigator, and this may have to be done by intuitive judgement. Non-glacierized portions of the drainage basin should have a sample point density equal to the density on the glacier. Sufficient density-depth profiles should be made to ensure that the areal variation in density is accounted for within the required 5 per cent accuracy.

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[*] A device that measures the arc of the sun as seen from any location, at any time of year.

[**] If ablation rates are low, arrays of stakes will be necessary at each measurement point. The numbers of stakes necessary at each point can be computed from the same statistical test mentioned earlier (Untersteiner, 1961, p.159-160).

On many glaciers the length of the ablation season will vary markedly with altitude. In this case, the usual stratigraphic system of ice balance measurements (Unesco/IASH, 1970b) yields results which cannot be clearly defined with regard to time. Thus these results cannot be related to heat and water balance results. However, by use of a combined system, the advantages of using natural horizons can be retained and the ice balance results can be directly related in time to other balance quantities. This combined system is described in the Appendix.

The following quantities should be measured and reported:

1. Monthly values of the ice balance, given separately as averages over glacier and whole drainage basin (millimetres of water-equivalent), are recommended.

2. Other ice balance quantities should be reported at end of season only, and given separately as averages over at least 8 intervals of altitude on the glacier only (millimetres of water-equivalent). These include:

a. Net or annual balance

b. Total or annual accumulation (alternatively, maximum or winter balance)

c. Total or annual ablation

3. These values are to be reported at end of season only:

a. Accumulation-area ratio or glacier ratio

b. Area of glacier and perennial snow and ice at end of balance year, and change from year before (km^2)

c. Length of glacier at end of balance year, and change from year before (km or m)

d. Altitude of the equilibrium line

4. Additional ice balance data can be obtained by measuring the ice-flow discharge through a cross-section of a glacier and comparing this with surface ice balance measurements made above or below the cross-section. This experiment is optional.

WATER BALANCE

Water run-off data are the only measurable parameters which are a true integration over the whole area of the drainage basin. Thus these data have a special significance: they can serve as a standard for the evaluation of the other area-sampled ice, water and heat balance results. Every effort should be made to obtain accurate run-off data, continuous in time over periods at least equal to the whole ablation season and preferably for the whole year.

Run-off data should be obtained at a gauging station (limnigraph) that has a relatively stable water level/discharge rating curve. Frequent calibrations (by current meter, salt dilution, or other technique) are necessary even after the rating curve has been established, to verify that no shifting of the rating has occurred.

The measuring procedure should be sufficiently accurate so that daily totals of run-off are measured with a standard error of less than 8 per cent under normal (ice-free) conditions, and monthly or twice monthly totals accurate to 5 per cent. At the beginning of the ablation season when ice and snow may cover the stream every effort should be made, by frequent flow velocity measurement, to reduce the error in daily totals to 10 per cent or less.

Daily values should be reported for as long a period during the year as measurements can be made, and should be given as millimetres averaged over the drainage basin area. In addition, twice monthly and monthly values (also in millimetres) should be tabulated.

In addition to run-off, a water balance computation requires knowledge of evaporation/condensation of water, rainfall, and the change of mass from ice to water (or vice versa). A large number of precipitation gauges, properly located and carefully utilized, together with accurate measurements of ice balance, may permit the estimation of evaporation/condensation. Alternatively, evaporation/condensation might be estimated from heat balance data obtained at the main site. Only by comparing all three balances, with careful attention to error magnitudes, can one obtain a valid and demonstrable description of how the ice mass in a glacier drainage basin changes in response to its external environment.

TOPOGRAPHIC MAP

An accurate, up-to-date topographic map is required in order to properly compile ice balance results and other areally distributed data. Thus it should preferably be compiled by air or terrestrial photogrammetry from pictures taken during the International Hydrological Decade. If the glacier is shrinking or growing markedly during this period, two maps may be required. Maps compiled from plane-table or other ground surveys will suffice if they meet the specific accuracy standards. The whole drainage basin should be mapped. The master copy of the map should be on scale-stable material (not paper).

Map scale and contour interval should be adjusted to the size and slope of the basin. For a basin 3 km in longest dimension, map scales 1:2,500 to 1:5,000 are appropriate, but if the basin is 6 km long, the scale should be

1:5,000 to 1:10,000. Larger scales are, of course, desirable but not necessary. The contour interval should be an even value which is about 1/100 or less of the total relief in the basin.

The accuracy of the map should be such that 90 per cent of the point locations have a horizontal position error less than 5 mm or 1 per cent of the scale, and the scale factor for the map as a whole should be correct to 1 per cent. The accuracy of vertical locations should be such that 90 per cent of the point elevations are correct to within half a contour interval.

3 SPECIAL STATIONS

The purpose of the Special Stations is to derive means of relating simple observations of air temperature, wind speed, etc., to the actual heat flux between atmosphere and snow surface. Accurate measurement of heat flux components is a very difficult and expensive task. These measurements cannot be expected as part of a routine programme at many stations. We hope that standardized observations at many stations can be related to the pertinent atmospheric processes through analysis techniques developed at the few Special Stations. Thus the Special Stations will be entirely research-oriented, and will have to be operated by extremely competent and knowledgeable meteorologists and glaciologists.

Special Stations can exist for heat balance work alone. That is, the area-wide ice balance and water balance measurements stipulated for Standard Stations are not required for Special Stations. However, it is absolutely essential that all Special Stations perform all the measurements listed under 'daily observations at one site' for Standard Stations, for the same period of time, and at the same (or better) levels of precision. Perhaps a Special Station will have to be operated on a site covered only by seasonal snow; that is permissible if the snow lasts sufficiently long into the summer so that useful data are obtained at the height of ablation conditions.

All major components of the heat balance are to be measured, directly or indirectly; incoming and reflected solar radiation, incoming and outgoing long-wave radiation, sensible heat flux from the air and precipitation, latent heat flux, heat flux from below the surface, and the mass (ice and water) flux. The techniques for doing this will be developed by the individual investigators, who also may experiment with empirical or theoretical relations between these measured quantities and the 'index' observations of the Standard Stations. It is hoped that the most modern sensors, such as sonic anemometers for eddy correlation measurements, and modern digitized data reduction systems can be used at some of these Special Stations.

These Special Stations are highly important: they are in fact the cornerstones for the whole programme. Although they will be expensive, the critical role they will play in the success of this major international effort should prove to be ample justification for sufficient funding, and in addition each station should make fundamental new contributions to our knowledge of micro-meteorology and air-snow interactions.

INSTRUMENT CALIBRATION

In order to analyse the data obtained at Standard Stations and to compare results on a hemispheric or global basis, it is necessary to have standard calibrations of instruments and methodology. Appreciable absolute errors cannot be tolerated. This standardization requires an international exchange of calibration data, and preferably on-site visits for national and perhaps international co-ordination and co-operation in devising proper techniques for producing really comparable results. Calibration results should be distributed along with data tabulations and station descriptions.

DATA EXCHANGE

Certain data from all stations will be of interest to all Combined Balance programme investigators on a current basis. These data should be transmitted to World Data Centres A, B, and C (Glaciology); certain summaries of results should also be transmitted to the Permanent Service on Glacier Fluctuations. Modern metric (SI) units are to be used throughout. Three different data reports should be transmitted to the Centres:

a. Station Description. This should be submitted only once unless major revisions are required, at the time of filing the first tabulation of daily values or annual summary. The following information should be given:

1. Name and location of station, principal investigator, sponsoring institute or agency
2. Dimensions (length, area, altitude range) of glacier
3. Dimensions (length, area, altitude range) of drainage basin
4. Major items of instrumentation and location
5. Calibration data on instruments
6. Supplemental or related stations (locations, instruments, frequency of observations).
7. Availability of data
8. Existing publications

b. Tabulation of Daily Values. This should be a table for each month giving daily totals or means of certain heat, ice, and water balance parameters. Most of these readings will be taken at the main site on the glacier. It is suggested that the data be submitted to the Centres as soon after the year of collection as possible. Copies of these standard tables can then be sent to interested investigators on request. It is recognized that these data are tentative, subject to possible revision by the individual investigator, and are not to be published without the express permission of the investigator(s) who collected them. The following daily totals or means are to be reported; results should be separated into daytime and night-time half-days if possible:

1. Global solar radiation and net solar radiation (MJ/m^2), or duration of sunshine (hours)
2. Cloudiness during daylight hours (tenths)
3. Air temperature at main site on glacier (°C)
4. Air temperature at other sites (°C)
5. Snow surface temperature (°C)
6. Nocturnal crust thickness (cm)
7. Wind speed (m/s)
8. Humidity (relative, specific, or dew point)
9. Precipitation as rain (mm)
10. Precipitation as snow (mm of water-equivalent)
11. Ablation (mm of water-equivalent)
12. Run-off
13. Other parameters, such as mean precipitation averaged over drainage basin

c. Annual Summary. This should be a tabulation of monthly or annual values of certain heat, ice and water balance quantities as mentioned in the text above, together with a list of new publications resulting from the project and any revisions in the Station Description.

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APPENDIX

A system to combine stratigraphic and annual mass balance systems

Most glacier mass balance data are collected through the use of stakes, pits, cores, or probing to or from a reference horizon. This is normally a summer horizon - either a winter snow/ice interface in the ablation area as measured in spring, or a snow/firn interface in the accumulation area as measured in spring or summer. This interface, termed summer surface, may form at different times of the year in different parts of the world or even on the same glacier.

In a pit or core in the accumulation area, the mass of ice material between two consecutive summer surfaces can be measured. This mass, in Mg/m^2 or metres of water equivalent, may be the balance (the difference between accumulation and ablation) at that point for the time interval between the formation of the two summer surfaces. However, in the percolation or soaked facies an appreciable part of the material deposited in this time interval may have been melted and subsequently redeposited (refrozen) in lower layers, below the lower of the two summer surfaces of interest. Detection of this problem is not easy, and analysis of the resulting balance may be even more difficult. It is assumed that any appreciable mass redeposited below a summer surface of interest can be calculated from repeated depth-density profiles and added to the balance above the summer surface.

A difficult problem in relating mass balance quantities to meteorologic and hydrologic quantities in this Combined Heat, Ice, and Water Balances programme stems from the fact that summer surfaces may form at different times in different places. This means that a simple integration over the glacier of mass balance data related to summer surfaces produces a result that has no clear meaning with respect to time. Thus these data cannot be directly related to heat or mass flux data obtained by other techniques.

Mass balance terms based on observable summer surfaces were proposed by Meier (1962). The stratigraphic system is a modification in terminology of the basic mass balance concepts. This stratigraphic system works well for individual points. However, in order to compare ice balance data with hydrologic (water balance) data, these point values must be integrated over a whole glacier or drainage basin. If, as is usually the case, the summer horizons are not formed synchronously over the whole area this integration is an invalid measure of snow and ice storage. Therefore, a different system, the annual system (fixed-date system), has been conceived to relate glaciological data to hydrological data. Unfortunately, glaciological programmes using only the annual system cannot take advantage of convenient reference horizons in the field, so the field work may be extremely difficult or exorbitantly expensive. These two systems are described in Unesco/IASH (1970b) but no attempt was made to show how they might be combined.

Presented here is a way to combine these two systems into a unified whole. The vital key to a combination of these systems is identification of the material under consideration. This identification is, of course, useful additional information for any description of the meteorological-hydrological environment. Four types of material which may be found on a glacier in one specific year are defined -- snow, old firn and ice, late snow, and new firn -- as follows: The highest (most recent) summer surface found in a pit dug in winter (or early spring) before the beginning of appreciable, continuous melting is termed ss_0. The material above ss_0 is termed snow (s) and the material below it is old firn and ice (i). The highest (most recent) summer surface found in a pit in the upper regions of the glacier calendar after the beginning of new snow accumulation following a period of melting in summer is termed ss_1. The material above ss_1 is now termed late snow (ls) and the material below ss_0 yet above ss_1 is now termed new firn (f). Superimposed ice formed during the year under consideration is included in snow (s).

The variation in these units of the mass balance may be illustrated by graphs showing the changing balance with time, b(t), at specific points on a glacier, expressed as mass per unit area (Mg/m^2) or simply in water equivalent (m) (Fig. 1). The balance quantities are designated by the letter b with qualifying symbols, as follows: the subscript $_0$ refers to the initial measurements made at or near the beginning of the year to relate fixed-date system measurements to stratigraphic units; the subscript $_1$ refers to the final measurements made at or near the end of the year to relate the two systems; the subscript a refers to certain measurements made (or calculated) exactly at the end of the hydrologic year, and the subscript n refers to measurements related to the minimum firn and ice or the minimum total mass near (but not necessarily at) the end of a hydrologic year; the letter x identifies balance quantities at the time of the maximum total balance in the hydrologic year. Letters in parentheses following the b indicate the material being measured. A lack of parentheses following the b indicates that the total mass (undifferentiated) is considered. The hydrologic year, often defined as 1 October to 30 September, runs from t_0 to t_1. Arrows pointing up indicate an addition of mass as time proceeds; the corresponding balance quantities are taken as positive.

Measurements made at specific points can be plotted as curves of balance changes with time (Fig. 1), and the following quantities can be defined:

1. $b_0(s)$, the initial snow balance, is the snow at the beginning of the hydrologic year.

2. $b_0(i)$, the initial ice balance, is the old firn and ice loss after the start of the hydrologic year and before ablation ceases in winter.

3. $b_m(s)$, the measured winter snow balance, is the snow above the summer surface ss_0 as measured directly by field work in late spring.

4. $b_1(ls)$, the final late snow balance, is the new snow at the end of the hydrologic year, the same as $b_0(s)$ for the year following.

5. $b_1(i)$, the final ice balance, is the old firn and ice loss after the end of the hydrologic year before ablation ceases for the next winter, the

same as $b_o(i)$ for the year following.

6. $b_n(f)$, the net firnification, is the amount of new firn formed at about the end of the hydrologic year (either just before or just after). It is therefore the mass between the successive surfaces ss_o and ss_1, and is usually measured in pits well after its time of formation.

7. $b_n(i)$, the net ice balance, is the corresponding change in mass between ss_o and ss_1 in the ablation area where this change is negative; thus it records the loss of ice and old firn from the end of one melt season to the end of the next.

8. $b_w(s)$, the maximum snow balance, is the hypothetical maximum mass of the snow during the hydrologic year. This value will occur at a different time at each place and thus will probably not be measured directly.

Mass balance data may next be considered in terms of diagrams showing the area-average balance curve b(t). Alternatively, one could plot the total balance curve B(t) using a different vertical scale of cubic metres instead of metres of water equivalent. In the material to follow, a bar over a symbol indicates an area average, as in Unesco/IASH (1970b).

A plot might be made of b(t) on which are shown the area-averaged values similar to the point values b_w and bn as given in Unesco/IASH 1970b). However, this scheme usually is not workable in practice. This is because the terms b_o, b_w, bn, and b_1 have no relation to the corresponding values measured relative to summer surfaces at the individual points. What is needed is a scheme in which the point data, taken only a limited number of times during a year and usually referenced to summer surfaces, can be combined directly. In order to do this, the summer surfaces must be included in the area-average diagrams. This is done by dividing the balance curve b(t) into its four components: old firn and ice, snow, new firn, and late snow (Fig. 2). The largest mass, old firn and ice, is plotted at the bottom -- it can only decrease or remain constant during any one year. Above it is plotted snow, which increases during the first part of the year; during the last part of the year it decreases due to ablation and is converted to new firn. Towards the end of the year, late snow is deposited on top of a melt surface, causing the snow below that surface to be converted to firn. The amount of new firn after all the snow is eliminated and/or converted remains relatively constant. The interface between (snow plus new firn) and (old firn and ice) is summer surface ss_o. The interface between new firn and late snow is summer surface ss_1. The interface between snow and new firn is shown as a jagged line; it has little physical significance.

The point data taken at specific times during the field season (or determined after-the-fact) can now be averaged over the glacier and shown on the area-average balance diagram (Fig. 2). Now a large number of balance terms can be precisely defined. One important quantity is the annual balance b_a. Another important balance quantity is the difference between old firn and ice melt, $b_n(i)$, the net ice balance, and snow which lasts through the melt season and is preserved as new firn, $b_n(f)$, the net firnification. This difference is here called the firn and ice net balance $b_n(fi)$. This is in fact the quantity most often reported by glaciologists as 'net balance' but is not the area-average net balance b_n indicated in Unesco/IASH (1970b).

The terms b_w (winter balance) and b_n (here termed the total mass net balance are analogous to the stratigraphic system point terms b_w and b_n in Unesco/IASH (1970b). The time interval t_o' to t_1' is a balance year which is unique to each glacier and each year, and is not necessarily 365 days long. Also included in this figure are the new terms b_x, the maximum balance, and $b_w(s)$, the maximum winter snow balance (of the hydrologic year). In order to relate b_n to b_a or vice versa, two additional terms are proposed: b_o, the initial balance increment, and b_1, the final balance increment.

On some glaciers, all the snow is normally converted to firn before the end of the hydrologic year, and it is convenient to measure firn and ice balances at this time. Therefore three additional terms are defined: the annual firnification $b_a(f)$, the annual ice balance $b_a(i)$, and the firn and ice annual balance $b_a(fi)$ (Fig. 2). These units are analogous to $b_n(f)$, $b_n(i)$, and $b_n(fi)$, respectively.

Other area-averaged terms shown on Fig 2, exactly equivalent to the corresponding values shown on Figure 1, are $b_o(s)$, the initial snow balance; $b_o(i)$, the initial ice balance; $b_1(ls)$, the final late snow balance; $b_1(i)$, the final ice balance; and $b_m(s)$, the measured winter snow balance.

The annual balance, b_a, is an important quantity because it represents the total change in storage (of snow, firn, and ice) during a hydrologic year. Thus this value can be compared directly with the difference between precipitation as snow and meltwater run-off, if net evaporation/condensation and net changes in liquid water storage are negligible. b_a can be measured directly, or computed as $b_a = b_a(f) \& b_a(i) - b_o(s) \& b_1(ls)$ if $b_a(f)$ is definable. The annual balance can also be calculated, more indirectly, from balance year (stratigraphic system) quantities as $b_a = - b_o(s) \& b_o(i) \& b_n(i) \& b_n(f) - b_1(i) \& b_1(ls)$.

It is important to define the maximum winter snow balance $b_w(s)$ on the glacier during the year, because it is often impossible to measure the actual winter snow accumulation. The term $b_m(s)$, a measured but lower value at about the right time of year, can often be used as a basis for computing $b_w(s)$ if sufficient supplementary meteorological data are available. The same statement can be made about b_w and b_x. Although b_w and b_x occur at the same instant in time, $b_w(s)$ can occur at a later date. Note that $b_x \& b_o = b_w$. Normally, only one or two of these four balance quantities ($b_w(s)$, b_w, b_x, or $b_m(s)$) would be reported. It must be stressed that none of these can be calculated by averaging point values of b_w (winter balance) because the balance reaches a maximum at different times at the different points.

These terms are listed and defined in Table I.

The apparent complexity of this scheme is somewhat misleading; only about half of these terms would be reported in any given study. All terms are shown on one diagram in order to make precise distinctions between quantities measured or reported. At many glaciers, some of the correction terms, such as b_o, $b_o(s)$, $b_1(s)$, $b_1(ls)$ and $b_o(i)$, will be zero or small, and if so can be neglected to simplify the calculations.

This scheme, although appearing somewhat cumbersome, gives the author a code for expressing whichever units he prefers in exact, definable and comparable terms.

Table I. -- Combined mass balance terms

Symbol	Name of term	Explanation
Stratigraphic system		
$b_m(s)$	Measured winter snow balance	Balance measured to the summer surface (ss_o) in late winter or spring, measured in pits, cores, and by probing.
$b_w(s)$	Maximum winter snow balance	Maximum of snow mass during the balance year, computed from graph of $b_s(t)$ or graphs of $b(t)$ and $b_i(t)$ before and after time of $b_m(s)$.
b_w	Winter balance	Maximum value of the balance in relation to balance at t_o'; amplitude of mass change during the balance year. Computed from changes in $b(t)$ before and after time of $b_m(s)$.
$b_n(f)$	Net firnification	The increment of new firn in the accumulation area, as measured after ablation ceases in autumn in pits or cores. Date ablation ceased indicated under value.
$b_n(i)$	Net ice balance	Old firn and ice melt in the ablation area of a single melt season, measured with stakes once during period when ice is covered by snow and again after ablation ceases.
$b_n(fi)$	Firn and ice net balance	Change in mass of firn and ice during a single melt season; the mass between two consecutive summer surfaces. $b_n(fi) = b_n(f) \& b_n(i)$.
b_n	Total mass net balance	Change in snow, firn, and ice storage between times of minimum mass; net change in mass during one balance year. $b_n = b_o - b_1 \& b_a$.
Terms relating annual and stratigraphic systems		
b_o	Initial balance increment	Change in balance between first time of minimum balance (t_o') and t_o; computed from graph of $b(t)$.
$b_o(s)$	Initial snow balance	Snow accumulated on summer surface (ss_o), measured at t_o with pits or cores.
$b_o(i)$	Initial ice balance	Old firn and ice melt in the ablation area after t_o and before melt begins the following spring, measured by ablation stakes at t_o and during period when ice is covered by snow.
b_1	Final balance increment	Change in balance between time of minimum mass (t_1') and the end of the hydrologic year (t_1), computed from graph of $b(t)$.
$b_1(ls)$	Final late snow balance	Snow accumulated on summer surface (ss_1), measured at t_1 with pits or cores.
$b_1(i)$	Final ice balance	Old firn and ice melt in the ablation area after t_1 and before melt begins the next spring, measured by ablation stakes at t_1 and during period when ice is covered by snow.

Symbol	Name of term	Explanation
Annual	(fixed-date system)	
b_x	Maximum balance	Maximum value of the balance in relation to balance at t_o; amplitude of mass change during hydrologic year. Occurs at same time as b_w. $b_x = b_w - b_o$.
$b_a(f)$	Annual firnification	The new firn formed on the glacier during the hydrologic year, measured at t_1 in pits or cores. Not definable if snow melt continues after t_1.
$b_a(i)$	Annual ice balance	Old firn and ice melt in the ablation area during the hydrologic year, measured by stakes at t_o and t_1.
$b_a(fi)$	Firn and ice annual balance	The change in mass of firn and ice during the hydrologic year from t_o to t_1, also the mass between two consecutive summer surfaces at t_1. $b_a(fi) = b_a(f) \& b_a(i)$.
b_a	Annual balance	Change in snow, firn, and ice storage between t_o and t_1; approximately the difference between precipitation as snow and meltwater run-off for one hydrologic year. Can be measured directly at t_o and t_1. $b_a = b_a(fi) - b_o(s) \& b_1(ls)$ if $b_a(fi)$ is defined.

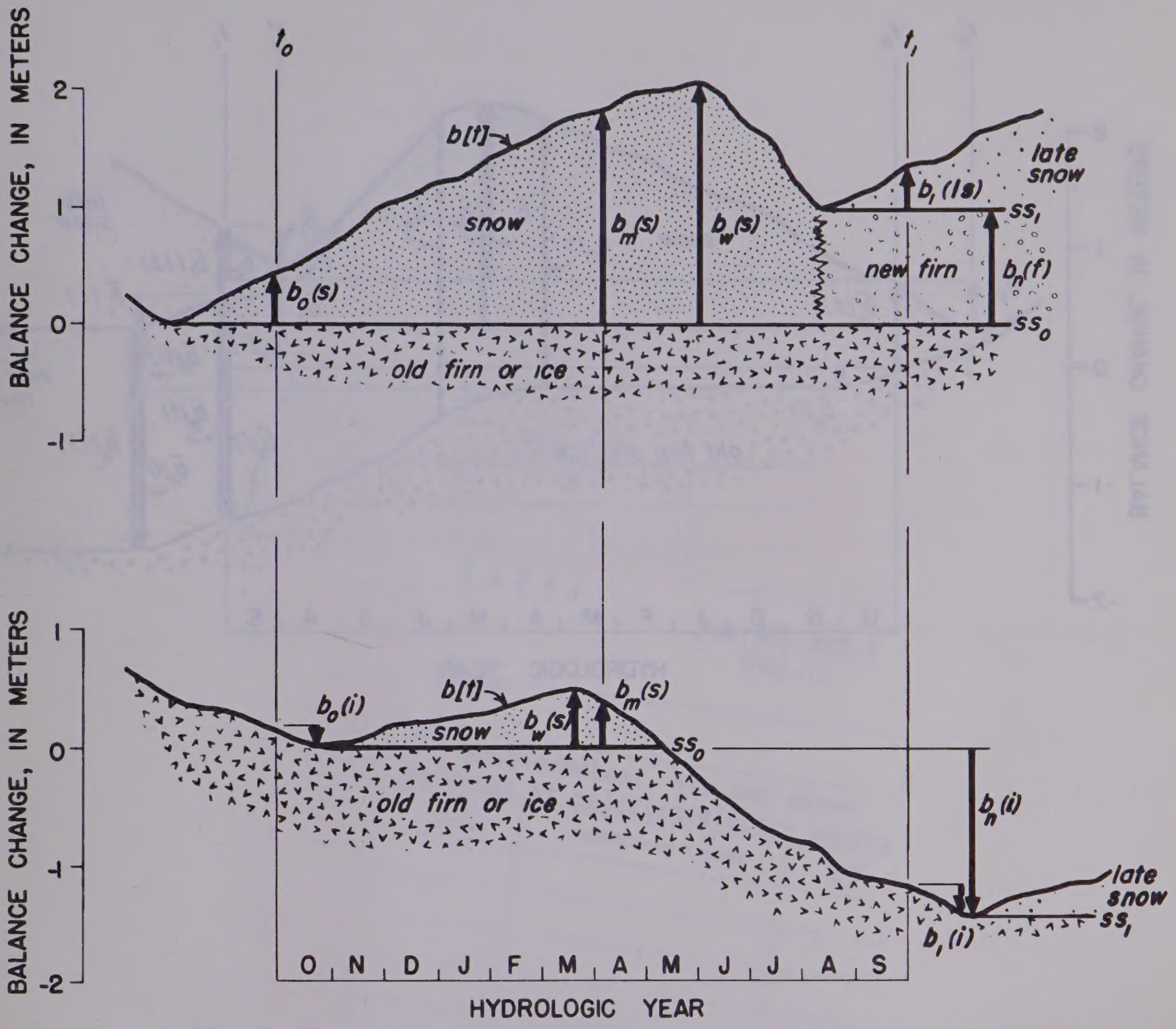

Figure 1.-- Balance quantities measured at a typical point in an accumulation area (above) and at a typical point in an ablation area (below). Vertical scale is metres of water-equivalent with an arbitrary zero.

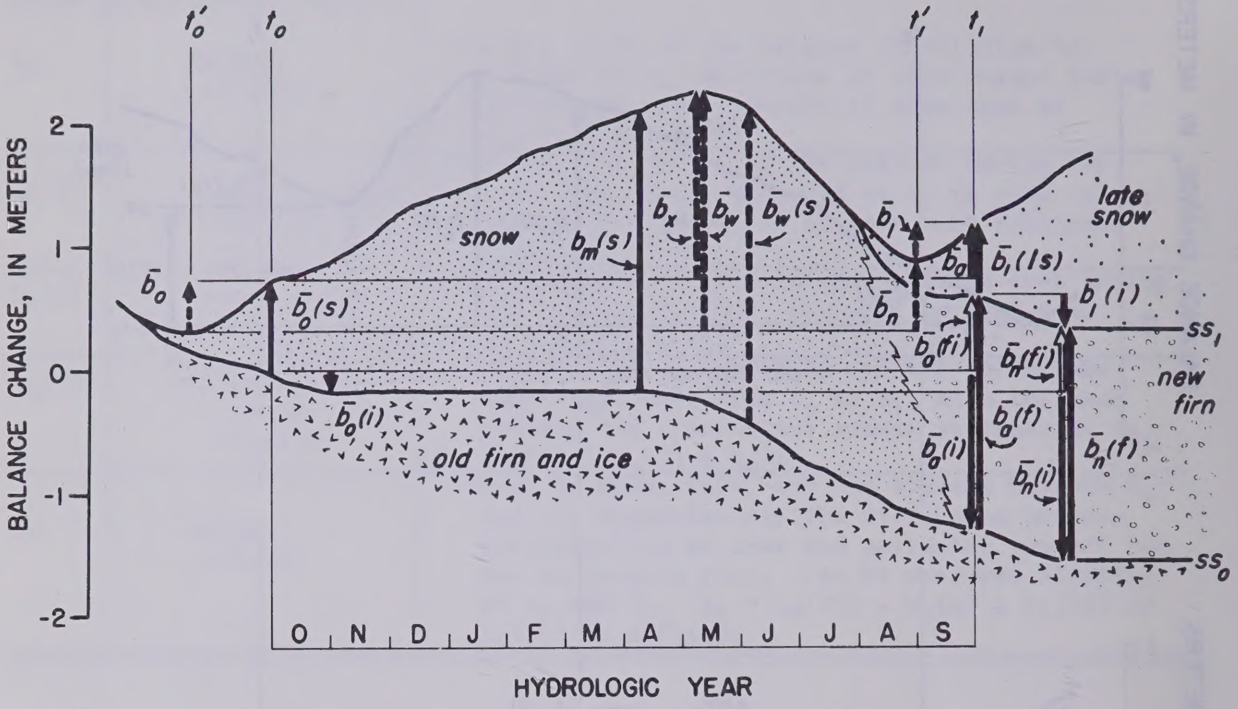

Figure 2. -- Area-averaged balances. All balance terms are shown on one diagram for reference purposes. No one programme should expect to report all these possible terms, but only those selected as most relevant to the particular environment and observational scheme. Conveniently measurable quantities shown with solid arrows, quantities derived from knowledge of the area-averaged balance curve b(t) shown with dashed arrows, calculated quantities shown with open arrows. Vertical scale is metres of water-equivalent with an arbitrary zero.

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